

A Complete Review of Ultrasonic Metal Welding, Ultrasonic Consolidation, and Additive Manufacturing Techniques

¹Dr. Samir B. Shah, ²Dr. Komal G. Dave

¹Assistant professor, Mechanical engineering department, L. D. College of engineering Gujarat, India

²Professor mechanical engineering department L.D. College of engineering Ahmedabad

DOI: <https://doi.org/10.51244/IJRSI.2026.13020007>

Received: 08 February 2026; Accepted: 13 February 2026; Published: 23 February 2026

ABSTRACT

For joining standardized metals and alloys, conventional fusion-based welding methods like electron beam welding (EBW), laser beam welding (LBW), friction stir spot welding (FSSW), and resistance spot welding (RSW) are frequently employed. Nevertheless, these procedures frequently experience uneven weld quality, thermal distortion, and metallurgical degradation because of high processing temperatures. Solid-state joining technologies, especially ultrasonic consolidation (UC) and ultrasonic additive manufacturing (UAM), have been developed as a result of these constraints. In order to create metallurgical bonds between metallic or non-metallic foils at almost room temperature, UC/UAM uses high-frequency ultrasonic vibrations under moderate normal pressure. This allows for the creation of low-temperature, multi-layered solid structures without melting the base materials.

By investigating the integration of ultrasonic metal welding (UMW) with electrical discharge machining (EDM) and other advanced machining techniques for improved manufacturability and design flexibility, this study seeks to close the gap between industrial welding practices and evolving manufacturing demands. In order to comprehend interfacial bonding mechanisms, optimize process parameters, and guarantee structural reliability, emphasis is placed on micro structural characterization and mechanical performance evaluation of UC/UAM-fabricated components. The results demonstrate how UC/UAM-based hybrid manufacturing techniques can be used to produce complex, lightweight, multi-material engineering components.

Keywords— Welding of Ultrasonic Metal, Electro Discharge, Consolidation of Ultrasonic, Additive Manufacturing of Ultrasonic

INTRODUCTION

The automotive, aerospace, electrical, and space exploration industries are among the major industrial sectors whose advancements have been accelerated by growing concerns about climate change, energy efficiency, and sustainable manufacturing. The need for lightweight, multi-material, high-strength components that can boost performance while consuming less energy has increased as a result of these advancements. As a result, materials like carbon fiber reinforced polymers (CFRPs), aluminum, titanium, magnesium, and copper are frequently used in contemporary engineering applications.

In this regard, the joining of dissimilar-lightweight materials is still one of the main challenges for the conventional fusion-based welding processes due to excessive heat input, thermal distortion, degradation in metallurgical properties, and residual stresses. In response to these limitations, ultrasonic metal welding has emerged as a promising solid-state joining process for the manufacturing of hybrid and multi-material structures. UMW realizes metallurgical sound bonds through the application of high-frequency ultrasonic vibrations under moderate normal pressure; bonding may be achieved through interfacial plastic deformation, localized slip, and oxide layer disruption without the melting of base materials.

One of the major advantages of ultrasonic welding is the lower thermal input. The lower thermal input eliminates distortion and reduces the alteration of the material properties. The lower thermal input actually makes this process ideal for joining thin foil materials and wires. In addition to this, it is also useful in joining different material combinations. Ultrasonic welding of thin foil and thick materials is a common example. Ultrasonic welding can be carried out in different welding modes. Some of the welding modes include spot welding, line welding, ring welding, and continuous seam welding. There are different critical process parameters.

In ultrasonic welding, frequencies of vibration lie between 10 kHz and 175 kHz, depending on the ultrasonic welding system used. In this process, bonding can be attributed to solid-state adhesion, which relies on oscillating shear forces and static normal pressure for generating plastic deformation at the weld interface. Ultrasonic welding has many applications in industries, but its bonding principles are still not clearly understood due to its complexity. Ultrasonic welding is one of the techniques used in ultrasonic processing. There are advantages of ultrasonic processing that can be discussed.

Alongside advancements in joining methods, there has been growing demand for micro-and macro-scale parts machined from difficult-to-machine materials such as titanium alloys, carbides, tool steel, and superalloys. Such materials are very difficult to process by conventional machining methods because of problems with work hardening, high temperatures generated during machining, reactivity, and poor heat conductivity. To overcome these issues, the use of electrical discharge machining (EDM) has been well received as the non-traditional machining technique that can accurately produce electrically conductive and semi-conductive materials regardless of their hardness. The EDM technique has been applicable in the production of complicated macro- and micro-scale details in the form of non-circular holes and complicated dies with high precision. This technique is of great use in the manufacture of micro-channel heat exchangers (MCHEs), which are widely used in energy-efficient air conditioning and refrigeration units. The aluminum-based heat exchangers ensure better sustainability in terms of environmentally conscious engineering practices because of the following reasons:

Presently, more and more research efforts are directed to the development of hybrid manufacturing approaches that incorporate ultrasonic metal welding with EDM and other advanced machining processes to overcome the existing limitations in manufacturing. This can help not only in decreasing the time of processing but also in enhancing the bonding quality and fabricating lightweight, multi-material components with structural, functional, and geometrical complexities, such as hollow and micro-channel devices. The continuous investigation for process parameter optimization, interfacial bonding mechanisms, and enhancement in overall efficiency and applicability will be advantageous for these advanced manufacturing technologies.

LITERATURE REVIEW

In this paper, Author is investigated the ultrasonic welding behavior of multilayer copper foils with nickel interlayers, employing copper foils with 0.2 mm nickel plating and 0.8 mm nickel foils. The welding specimens had dimensions of 20 mm × 50 mm, with foil thicknesses ranging from 8 μm to 0.2 mm. The study focused on the influence of weld time, vibration amplitude, and welding pressure on joint quality. The results illustrated that high fastening energy combined with ≥ 3.0 bar welding pressures and welding times below 0.5 s realized strong and consistent metallurgical bonds, indicating the importance of energy-pressure synergy in the ultrasonic welding process [1].

In paper present the dynamic weld forming process in the ultrasonic welding of materials was analyzed through high-speed imaging [2]. For imaging, the Phantom v1610 high-speed camera mounted with binocular lenses was used. In the experiment, the 1.0 mm thick copper sheet was placed on the anvil and overlaid with four nickel-plated C11000 copper foils having 0.2 mm thickness. Using the 50 lb/in² clamping force and the 60 μm sonotrode vibration amplitude, the authors studied the oscillations in the sheets and the bond produced. As per the findings, coarse anvils produced more bond density along with greater strength than the fine and medium anvils. Additionally, the tool lifetime was significantly enhanced.

In the paper author studied hybrid additive manufacturing based on ultrasonic consolidation using commercially available layered materials. The used system consisted of an Al 3003 base plate and a sonotrode in titanium

alloy with a diameter of 5.8 inches. The following foils were used: annealed SS 316L (0.004 in), Cu 110 (0.005 in), Al 3003-H19 (0.006 in), and Al 1100 (0.005 in). Joining of the foils was done by using ultrasonic welding equipment from Solidica Inc. (USA). The hybrid manufacturing platform was designed by integrating a three-axis CNC machining system, automated feeding of foils, ultrasonic welding unit, CAD-based toolpath generation, foil-trimming mechanisms, and heated base plate to enable the feasibility in the creation of functionally graded and multi-material structures by using the ultrasonic additive manufacturing process.

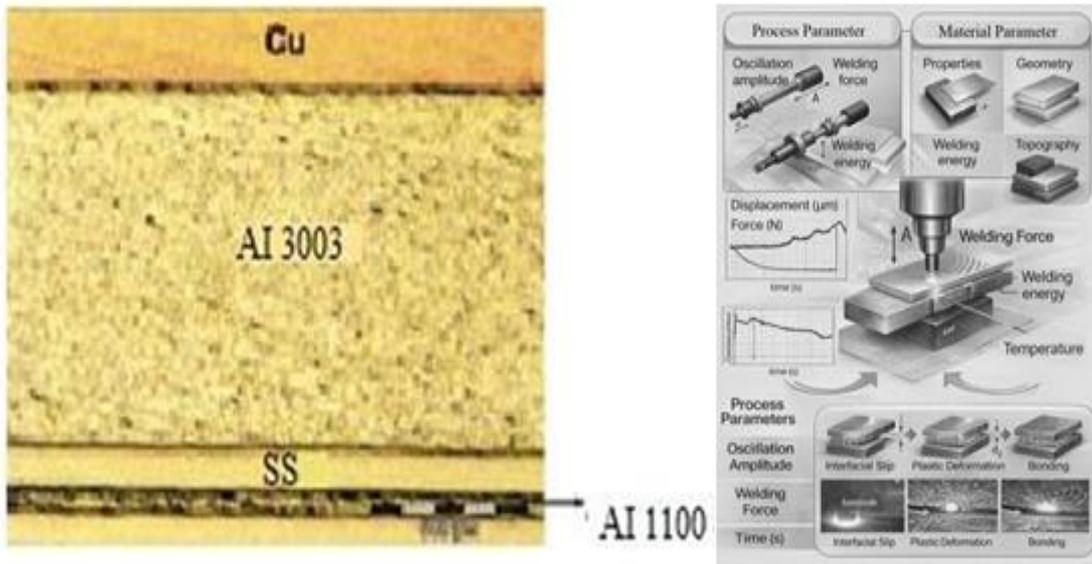


Figure 1 Theoretical Microstructure of the FGM Figure-2: fundamental elements in ultrasonic metal welding In this paper, the possibility of ultrasonic welding in hybrid material systems, including ceramic, glass, aluminum alloys, glass fiber reinforced plastic (GFRP), and carbon fiber reinforced plastic (CFRP), has been proven by the author. The welding time took less than 1 second for metals, glass, and ceramic material and under 4 seconds for composite materials. The tensile strengths of up to 50 MPa were measured by the authors, confirming the ultrasonic welding capability in making sound joints for both metallic and non-metallic materials [4].

In this particular case, the researcher of interest has examined the ultrasonic welding of Al1100 aluminum and C110 copper, specifically addressing the impact of welding energy, force, and amplitude on bonding quality within a closed-loop ultrasonic welding process seen in figure 1[3]. The analysis of interfacial characteristics was carried out through transmission electron microscopy analysis, scanning transmission electron microscopy analysis, high-resolution transmission electron microscopy analysis, and EDS analysis. The work has provided important insights into interfacial microstructural developments and bonding from a metallurgical perspective within ultrasonic welding [5].

In this article, the ultrasonic welding of thin sheets of different metals with a focus on copper and nickel-coated copper foil with a thickness of 0.2 mm and nickel layer thickness of 3 μm was examined by the author is illustrate in figure 2. The dimensions of the specimens were 45 mm x 25 mm, with T-peel strength used to assess weld quality. In this case, a factorial design was used to investigate the weld pressure and weld time. Based on the data from peel strength and maximum load, welds were ranked into five classes to establish a weldability lobe chart. The optimum welding conditions were derived by making use of third-order polynomial regression-based response surface analysis to predict exactly weld strength and sensitivity seen in figure 3[6].

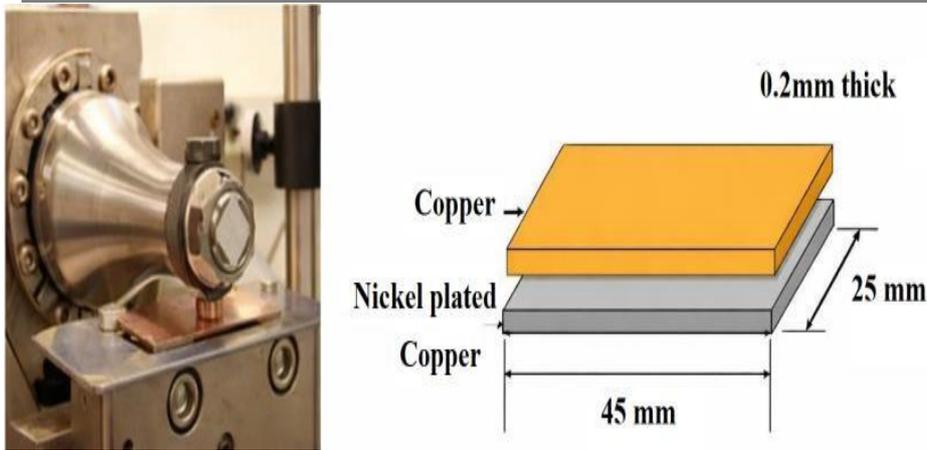


Figure 3 Mechanism for welding and specimen to examine

EDM (Electrical Discharge Machining)/Wire-Cut

This investigation focused on the properties of wire electrical discharge Machining for Aluminum 6061 alloy on a CNC wire-cut EDM EX7732 machine. A zinc-coated brass wire with a diameter of 0.25 mm and a strength of approximately 900 N/mm² is employed. Prior to the machining process, the wire is programmed to be lined up according to the desired perimeter shape of the material. The surface finish of the machined samples was determined by SJ-201P surface roughness tester [7].

The study mainly focused on the influence of the basic electrical process parameters, which include the maximum discharge current in amperes (A), pulse ON-time in microseconds (Ton), and pulse OFF-time in microseconds (Toff), and tries to investigate the machining performance through material removal rate (MRR) as the principal response parameter. From the experimental result, it is clear that MRR increased with an increment in pulse ON-time from 20 μ s to 40 μ s due to the increased discharge energy per spark. However, a higher pulse ON-time resulted in irregular sparking and reduced the efficiency of machining.

Raising the pulse OFF time from 3 μ s to 6 μ s increased the MRR as it provided sufficient time for the evacuation of debris as well as dielectric recovery between the pulses. Increasing the pulse OFF time to 9 μ s led to a reduction in the MRR as it provided an ample amount of idle time and reduced the rate of sparks. Similarly, an increase in the peak current from 1 A to 2 A increased the MRR as the intensity of sparks increased; beyond this point, the MRR started decreasing as the wire became unstable.

The best machining performance occurred when pulse ON time is set to 20 μ s, pulse OFF time to 3 μ s, and peak current to 3 A. This experiment proved that optimization of electrical parameters is an essential factor to enhance machining production and surface integrity in WEDM machining of aluminum alloys.

The performance capability of wire electrical discharge machining (WEDM) process on Aluminum 8011 alloy material was investigated by using a CNC EDM machine. For the purpose of this study, brass wire electrodes containing Cu 63% and Zn 35-37% are used, with deionized water as the dielectric fluid, as shown in fig. 4. The selection of the brass wire material for the study was based on the high electrical conductivity, tensile strength, and stability to high temperatures, all of which are essential for ensuring that the wire provides continuous electrical discharge during high-speed cutting operation.

The authors emphasized that in successful WEDM processes a continuous strong spark discharge is required, and it is greatly affected by the conductivities of the work material and the electrode. Test materials that display high levels of electrical conductivity can conduct energy from the power source to the machining area quickly, which improve machining speed and material removal rates. This study further reiterated the importance of considering the diameter of the wire, stating that a 0.3 mm diameter of the wire is preferably used in rough cutting in order to have greater cutting speeds, as well as using a 0.2 mm diameter of the wire in finish trimming in order to have better accuracy and surface finish.



Figure 4 Set up of W-EDM

Table 1. Chemical Configuration of Aluminum Alloy (wt.%)

| Element | Al (%) | Si (%) | Fe (%) | Cu (%) | Mg (%) | Mn (%) |
|-------------|--------|--------|--------|--------|--------|--------|
| Composition | 89.50 | 0.296 | 0.236 | 0.043 | 0.096 | 0.064 |

Table 2. Physical and Mechanical Possessions of Aluminum

| Property | Value | Unit |
|----------------------------------|--------|-------------------|
| Density | 2.6898 | g/cm ³ |
| Melting Point | 660 | °C |
| Boiling Point | 2480 | °C |
| Coefficient of Thermal Expansion | 23.5 | μm/m•°C |
| Atomic Weight | 26.98 | g/mol |
| Modulus of Elasticity | 68.3 | GPa |

Table 3. Elastic Possessions of Aluminum

| Property | Value (GPa) |
|-----------------|-------------|
| Young's Modulus | 70 |
| Shear Modulus | 26 |
| Bulk Modulus | 76 |

Assumption of the study showed that the proper selection of material for the electrodes, wire size, and dielectric fluid is critical for improving WEDM for Aluminum 8011 material see in Table 1. The study results are of major significance in understanding ways to improve machining efficiency and surface integrity in WEDM of Aluminum material see in table2 and table 3.

One area where the efficiency of wire electrical discharge machining (WEDM) is remarkably influenced is the use of wire electrodes such as brass wire and molybdenum wire, as they have special machining characteristics. Through systematic variation of critical process parameters, the effect of machining factors on productivity and surface integrity was investigated. It was revealed that machinability was decreased with molybdenum wire electrodes owing to higher material removal, but they provided superior surface finish and accuracy than brass wire electrodes.

On the other hand, the material removal rates (MRR) attained by the brass wire electrodes were better because of the improved sparks and the efficiency of energy transfer. Based on the Taguchi DOE method, the authors have been able to identify the best and worst machining parameters for the WEDM of Aluminum 8011 material. This has been achieved for maximum and minimum material removal rates during peak current values of 1 to 3 amps, pulse ON time of 32 to 36 microseconds, and pulse OFF time of 6 to 7 microseconds.

Ultrasonic Additive Manufacturing (UAM)

Ultrasonic Additive Manufacturing (UAM) on the ALPHA UAM system, identifying welding speed (mm/s), normal pressure applied (kPa), and amplitude of oscillations of the sonotrode (μm) as the most significant factors affecting the quality of interlayers joining. To evaluate the bond between the layers, the parameter Linear Weld Density (LWD) was used, calculated as follows:

$$LWD\% = \frac{L_b}{L_c} \times 100$$

L_c

Here, L_b represent the effective length of bonded and L_c length of total interfacial contact

Mechanical peeling tests were conducted using a universal tensile testing machine to measure bond strength. The results obtained were subjected to statistical analysis to determine how LWD values correlate to mechanical properties. Further studies conducted by researchers at Loughborough University showed that there is a dynamic interaction between a sonotrode and interfacial foils that affects surface topography. These findings are confirmed based on an analysis using LWD tests, peel tests, optical microscopy, and white light interferometry studies, with white light interferometry being used to independently validate surface deformation mechanisms. These results prove that bond mechanisms in UAM processes are controlled by localized plastic deformation and disruption of interfacial asperities, not based on melting [9].

The bonding ability of UAM through the Alpha 2 UAM System consists of several processes, which include the ultrasonic welding unit, the anvil, the pneumatic foil tensioning system, as well as a customized clamping system. The use of the pneumatic system aided in the directional control of the forces in preventing buckling. The experimental setup involved an oscillation amplitude for the sonotrode of 18 μm , a normal force of 1600 N, and a linear welding speed of 30 mm/s. Experimental runs progressed in three different phases. In the initial phase, block-shaped restrictions were applied to study foil extension. In the other phases, there were no restrictions on foil deformation.

The aluminum foils were cut with a defined distance to the start of the welded bond, and measurements were made concerning distortion and recovery prior to forming and bonding. Experiments have revealed the effectiveness of UAM in simultaneous forming and bonding, emphasizing the ability to form to a defined dimension in the weld path seen in figure 5. The positional and geometric variation in the multilayer formation was found to be within a boundary of 5–7%, which is acceptable for a multi-layer product in relation to forming dimensions and positional deviation [10].



Figure 5 Machine version alpha 2 of UAM

The process of bond formation in Ultrasonic Consolidation (UC) using a Solidica Formation UC system was investigated. The experimental setup used a titanium sonotrode with a diameter of 147mm and was subjected to controlled ultrasonic vibrations. Aluminum alloy 3003 was selected as the material in the UC process. The aluminum foils supplied by Solidica were known for their thickness of 150µm, width of 25mm, and H18 temper status.

The authors identified that in order for a reliable ultrasonic bond to be made, two important conditions must be met: (i) the establishment of a high degree of contact between clean metal surfaces, and (ii) the application of sufficient interfacial plastic strain to overcome surface oxide layers. These conditions were satisfied using the effective control of critical process variables, such as: sonotrode amplitude of oscillation (µm), welding velocity (mm/s), magnitude of the applied force (N), and interfacial surface temperature (°C). Through this, strain-induced deformation of localized surface asperities and oxide fragmentation were encouraged, thereby enabling solid-state metallurgical bonding without bulk melting thresholds. The technology was proved to be principally Founded on mechanical interfacial activation, in opposition to diffusion mechanism principles [11].

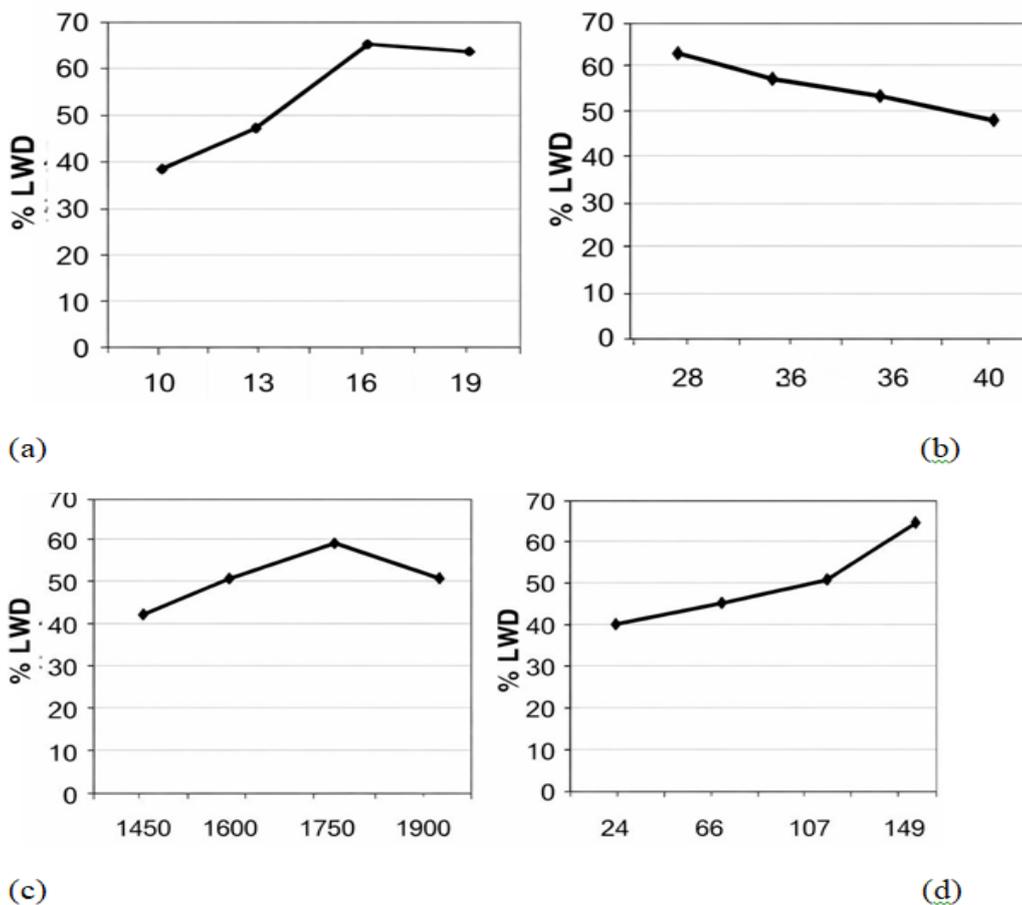


Figure 6 The effect of welding situations on direct weld density: (a) LWD vs Oscillation amplitude and (b) LWD vs, Welding speed, (c) LWD vs. Normal force, (d) LWD vs. Substrate temperature

Role of Process Variables on Linear Weld Density (LWD)

In the relationship between ultrasonic weld density and pulse duration, an increase in the latter leads to a gradual rise in ultrasonic density and a reduction in Linear Weld Density (LWD).

A graph showing the relationship between ultrasonic welding:

(a) Effect of Oscillation Amplitude

With an increase in the amplitude of sonotrode oscillations from 10 to 16 µm, there was an accompanying increment in the value of LWD, which signified an increase in the interface plastic deformation and disruption

of surface layers of oxides. But an increase in amplitude to a further value of 19 μm showed a slight decrease in the value of LWD. Such a trend indicates that higher vibrational amplitudes can cause interface slippage and may resist metallurgical bonding.

(b) Effect of Welding Speed

Correlation between welding speed and LWD: Correlation exists between the welding speed and the LWD, as low welding speed (40-28 mm/s) significantly enhances the binding process. Maximum LWD is attained by the lowest welding speed, i.e., 28 mm/s. This is attributed to the increased time of the interface between the sonotrode and the foil due to the low speed.

(c) Result of Normal Force

With the increase in the applied normal force from 1450 N to 1750 N, the LWD was improved because of the increased deformation of the asperities and the greater real contact area. But the increase in the applied force from 1750 N to 1900 N caused a major reduction in the LWD. High force might cause abnormal surface stresses that could cause damage to the joint surface.

(d) Effect of Substrate temperature

It was observed that the LWD increased consistently with an increase in substrate temperature ranging from 24°C to 149°C. With an increase in substrate temperature, material flow stress decreases, which allows for easier localized plastic deformation and improvement in interfacial bonding without attaining melting conditions.

Most of the components manufactured in this work were made with Aluminum alloy 3003 in its monolithic form or combined with other metals and alloys to enhance functional behavior. Several reports have demonstrated that ultrasonic welding between Al 3003 and other Al-Cu alloys, AMC, and Ni-based alloys resulted in enhanced properties at their interfaces. Further, SiC fibers and stainless-steel wire mesh embedded within an Al 3003 matrix have also been successfully integrated into UC/ UAM-manufactured multifunctional metal matrix composites. [11]

Distortion Possessions of Ti-Al Laminate Metal Composites

A study conducted by Irfan Kaya et al. tested the formability and mechanical properties of thin Ti-Al LMCs prepared via Ultrasonic Additive Manufacturing (UAM). The work used 127 μm -thick commercially pure titanium and Al 1100 foil. The thickness of bi-metallic three-layer, five-layer, and seven-layer samples was 0.889 mm, 1.397 mm, and 1.905 mm, respectively, with Ti on top and bottom.

For mechanical testing, specimens with two different orientations have been produced. These are Type A specimens that are parallel to the vibration of the sonotrode, while the other specimens are Type B, which are parallel to the motion of the sonotrode. The specimens have all been cut with the surface facing the sonotrode. Tensile specimens have been produced in accord with ASTM E8-04 guidelines through abrasive water jet cutting.

The uniaxial and biaxial deformation of the LMCs was tested at 25°C, 100°C, 200°C, and 300°C and at strain rates of 0.0013 s^{-1} and 0.013 s^{-1} . Test results showed that mechanical properties degrade rapidly in thin Ti-Al foils with increased temperature because of thermal softening. Ultimate tensile strength was insensitive to specimen orientation. Seven-layer laminates exhibited higher strength and ductility compared with single-layer or lower-layer-count samples, which demonstrated the beneficial effect of multilayer architectures on mechanical performance [13].

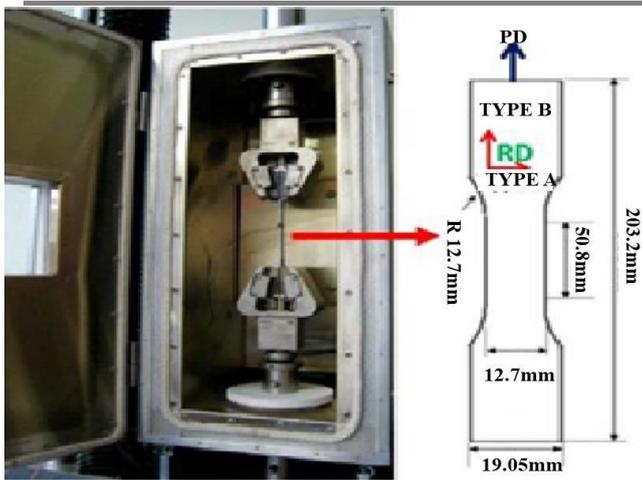


Figure 7 Test device of Warm tensile test and specimen dimensions

Ultrasonic Additive Manufacturing (UAM) is a solid-state, metal additive manufacturing process that uses ultrasonic metal welding to produce metallic parts at a temperature close to room temperature, thereby avoiding any defects that could be generated in the process of melting metals. Aluminum alloy 6061-H18 thin sheets of 0.006 in(0.1524 mm) thickness and 1 in(25.4 mm) width were ultrasonically bonded together with an Al 6061-T6 base plate, which ensured the provision of necessary strength during the deposition process.

The Al 6061-H18 foils used in this experiment are subject to initial annealing, then cold working to produce an H18 temper. This leaves it strain-hardened with a high density of dislocations. Taking advantage of T6-substrate temper allows examination of interfacial binding between materials under different metallurgical conditions. The application of methods like heat treatment and simulation of aging serves for analysis aimed at determining the influence on mechanical properties or microstructural alteration in UAM-processed parts. Results from this study confirmed that UAM is an efficient method for binding high strength Al alloys to each other while preserving material integrity because of its minimal temperature input and solid state processing nature [14]. Here welding parameter of UAM is mention in Table 4.

Table 4 Welding parameter of UAM builds

| Welding Parameter | Value |
|-----------------------|------------------------|
| Normal Force | 5000 N |
| Oscillation Amplitude | 32.8 μ m |
| Welding Speed | 200 in/min (84.6 mm/s) |

Table 5 Tensile Test Results for Overlap and Stacking Study

| Specimen | 1A | 1B | 1C | 1D | 2A | 2B |
|-----------------|-------|-------|-------|-------|-------|-------|
| Test 1 (MPa) | 133.1 | 121.7 | 202.3 | 227.1 | 225.1 | 185.1 |
| Test 2 (MPa) | 117.7 | 129.8 | 214.7 | 178.8 | 177.5 | 196.3 |
| Test 3 (MPa) | 124.0 | 144.2 | 211.4 | 228.2 | 185.1 | 167.7 |
| Mean (MPa) | 124.9 | 131.9 | 209.5 | 211.4 | 196.0 | 183.0 |
| Std. Dev. (MPa) | 7.7 | 11.4 | 6.4 | 28.2 | 25.8 | 14.4 |

The ultimate tensile strength test data calculated and generated for the mechanically correct specimens are presented in Table 5. Tensile test results in Plate 1 are clear in their differentiation of the mechanical behavior of groups A and B from groups C and D.

In Group A samples, the average value for tensile strength was about 128 MPa, and this was appreciably lower in value compared with Groups C and D, both of which closely approached a value of 210 MPa. This indicates that there exists a significant correlation between the tensile properties and the stack pattern and the method of overlapping used during the UAM process. A later set of tensile testing on Plate 2 also confirmed this observation as Build C showed the highest value on average for UTS to be 222.5 MPa. This suggests that the optimized stacking approaches have a major impact on improving the bonding and load transfer efficiency between layers in components made by UAM.

Based on the results, the optimal configuration for building UAM was found to be a random stacking sequence with a maximum layer stagger of 0.3 in (7.62 mm) and a tape-to-tape overlap of a minimum of 0.0025 in (0.0635 mm). Furthermore, the welds produced from a sonotrode having a surface roughness of 14 μm Ra exhibited enhanced mechanical strength compared to welds produced from a sonotrode of 7 μm Ra due to the enhanced interfacial friction and plasticity of the ultrasound-assisted welded samples.

Moreover, it has been reported that post-weld heat treatment operations such as the T6 temper state improved the strength of the components produced via the UAM process. In the T6 state, the tensile strength of the material is found to be nearly equal to the strength of the conventionally processed material. Furthermore, the researchers stated that better process parameters can be used to improve the efficiency of the components produced via the UAM process in the future [14].

From the outcomes of the experiments conducted, it was indicated that the optimized build process of the Ultrasonic Improver Manufacturing process should have a Foil Placement Strategy that is random with the maximum stagger of the stack to be 0.3 in or 7.62 mm and the minimum overlap from tape to tape of 0.0025 in or 0.0635 mm. This helps in the even distribution of stress to affect the structure positively.

Furthermore, the welds achieved with the sonotrode with a surface roughness of 14 μm Ra had better mechanical strength compared with the sonotrode with a surface roughness of 7 μm Ra. The reason is the increased frictional force, effective oxide layer disruption, and localization of plastic strain in the case of ultrasonic welding. Also, the post-weld heat treatment applied, particularly to reach the T6 temper condition, significantly enhanced the mechanical strength of components built by UAM. The tensile properties obtained in the T6 state were comparable to those obtained with conventionally processed bulk aluminum alloys, showing effective recovery and precipitation hardening after the UAM process. In addition, the authors have pointed out that a good optimization of processing parameters and component design can be very successful in further enhancing energy efficiency, mechanical performance, and functional reliability of the parts produced by UAM for advanced structural applications [14-17].

Ultrasonic Consolidation (UC) of Aluminum alloy 3003:

The study investigates the effects of critical process variable values on bonding and welded joint quality in ultrasonic consolidation of Aluminum alloy 3003. In ultrasonic consolidation, bonding is a result of elastic-plastic deformation, which occurs in the interface of the foil, which is created under combined normal static pressure and the resultant oscillating shear stresses caused by high frequency and low amplitude vibration cycles in the ultrasonic oscillator. These conditions promote the fragmentation and disruption of the naturally present aluminum oxide layer, thus increasing metal-metallic contact for metallurgical bonding in the solid state.

The UC system was capable of precise control of three significant process variables: the speed of the weld, the contact pressure, and the amplitude of oscillation of the sonotrode. The strength and integrity of the weld were measured through a combination of lap-shear and peel tests and microstructural analysis. Samplings were made using aluminum foil of the aluminum alloy 3003-H18 and had dimensions of width is 24 mm and initial thickness of 100 μm with no prior surface preparation. The values of the contact pressure were varied from 138 to 241 kPa (20-35 psi), with an increment of 35 kPa (5 psi). The values of the sonotrode oscillation amplitudes were set at

6.8, 8.4, 10.4, 12.3, and 14.3 μm , representing an amplitude setting from 10-90% in 20% increments, thus representing the dynamic capabilities of the UC system.

Two welding speeds are selected to demonstrate different regimes in the UC process. A high welding speed is considered to be 34.5 mm/s, while a low welding speed is considered to be 43.5 mm/s. For each combination of process parameters, five samples are made. These are necessary to ensure that statistical levels of reliability exist in terms of UC process repeatability. Results obtained from the experiment are validated in terms of both international and UK standards [18].

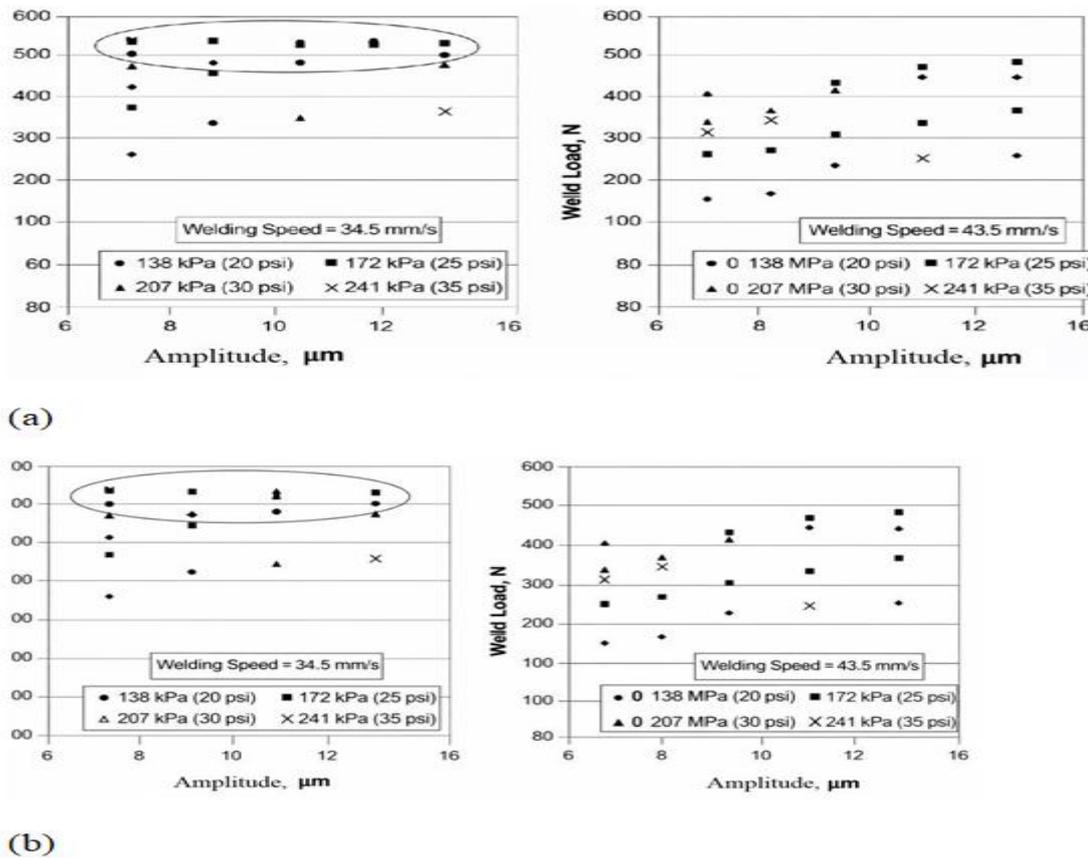


Figure 8 (a) Test result of Lap Shear & (b) Test result of Peel of different parameter

Figure 8 shows the failure forces of ultrasonic weld specimens made under different contact pressures and welding speeds. For the specimens welded at 138 kPa and 172 kPa over both welding speeds and those welded at 207 kPa with a welding speed of 43.5 mm/s, the failure load reached a peak value of approximately 570 N, as shown in Figure 8(a). An increase in contact pressure and oscillation amplitude led to a failure load decrease due to excessive foil distortion and localized interfacial damage, which induces early bond degradation.

On the other hand, the welding at lower traverse speed of 34.5 mm/s with a contact pressure of 207 and 241 kPa (30 and 35 psi) and oscillation amplitude within the range of 8.4 to 14.3 μm exhibited the highest peel resistance as depicted in Figure 8(b) by the highlighted area. The increase in peel strength with lower welding velocities is a result of the time of interaction between the sonotrode and the foil interface, leading to an increased plastic deformation, thus enhancing bonding at the interface.

The peel resistance tended to enhance with the increase in the amplitude of oscillations, which indicates the effective disruption of the oxide layers on the surfaces and better metallurgical interfaces. However, with the highest amplitude setting of 14.3 μm , the decrease in the peel resistance may be attributed to the vibrational energy that results in interfacial slip/microstructure damages. In the case of multiple layers, they proposed that the impact test of the multilayer sample, particularly those with more than 20 layers of foils, might provide an even more realistic assessment of the integrity or capacity of the interlinear bonds and the energy absorption ability. This method of testing could better assess the effect of the stacking and bonding process of the thick UAM parts [19,20].

CONCLUSION

Ultrasonic metal welding (UMW), together with ultrasonic consolidation (UC) and ultrasonic additive manufacturing (UAM), is an effective solid-state welding method for thin metallic foils with high bonding strength for Al, Cu, Sn, Mg, and CFRP. The qualitative bonding strength of UMW is verified through peel tests, tensile tests, linear weld density tests, and microscopic analyses.

Integration between UMW and Electrical Discharge Machining (EDM) can significantly eliminate production time and make it easier to produce complicated hollow parts or light-weight micro heat exchangers. There is an urgent need to optimize parameters, including amplitude values, processing speed, and pressing force, in order to ensure that it possesses optimal mechanical properties. Synergistic effect between UMW and EDM makes it possible to strictly control bonding between layers and retain material properties. Above-mentioned technology is an example that can lead to an efficient way to produce high-strength metal multilayer materials.

REFERENCES

1. Seungmin Shin, Angwoo Nam, Jiyoung Yu, Iyong Park, Dongcheol Kim, "Ultrasonic Metal Welding of Multilayered Copper Foils to Nickel-Plated Copper Sheet in Lithium-Ion Battery Cell", *Metal*, 2021, 11, 95, <https://www.mdpi.com/2075-4701/11/8/1195>.
2. S. Shawn Lee, Wayne Cai, "Analysis of Weld Formation in Multilayer Ultrasonic Metal Welding Using High-Speed Images," *Journal of Manufacturing Science and Engineering*, June 2015, <https://doi.org/10.1115/1.4029787>.
3. S. Kumar, "Development of Functionally Graded Materials by Ultrasonic Consolidation," *CIRP Journal of Manufacturing Science and Technology*, Vol. 3, Issue 1, 2010, pp. 85–87, <https://www.mdpi.com/2075-4701/9/5/505>.
4. Guntram Wagner, Dietmar Eifler, Frank Balle, "Ultrasonic Welding of Hybrid Joints," *JOM*, Vol. 64, No. 3, 2012.
5. Kaifeng Wang, Zijao Zhang, Jingjing Li, Qian Yu, Wayne Cai, "Investigation of Interfacial Layer for Ultrasonic Spot Welded Aluminum to Copper Joints," October 2017.
6. T. H. Kim, J. P. Spicer, J. A. Abell, J. Yum, S. J. Hu, "Process Robustness of Single Lap Ultrasonic Welding of Thin, Dissimilar Materials," *CIRP Annals-Manufacturing Technology*, Vol. 60, No. 1, 2011, pp. 17–20.
7. Satyam Tiwari, Mohd Saif, "Optimization of Wire Cut EDM of Aluminum Alloy 6061 Using Taguchi's Approach for Maximizing MRR," August 2020.
8. A. Elanthiraiyan, S. Ashok Kumar, S. Sathiyaraj, G. Antony Casmir Jayaseelan, "Investigation of Machining Characteristics of Aluminum 8011 by Wire Cut EDM Process", *AI-Khwarizmi Engineering Journal*, ISSN: 1818-1171, E-ISSN: 2312-0789.
9. R. A. Harris, R. J. Friel, "Ultrasonic Additive Manufacturing: A Hybrid Production Process for Novel Functional Products," *The Seventeenth CIRP Conference on Electro Physical and Chemical Machining (ISEM)*, 2013, pp. 35–40.
10. Alkaios Bournais Varotsis, Daniel S. Engstom, Ross J. Friel, Russell A. Harris, "Ultrasonic Additive Manufacturing as a Form-Then-Bond Process for Embedding Electronic Circuitry into a Metal Matrix," *Journal of Manufacturing Processes*, Vol. 32, 2018, pp. 664–675.
11. G. D. Janaki Ram, Y. Yang, B. E. Stucker, "Effect of Process Parameters on Bond Formation During Ultrasonic Consolidation of Aluminum Alloy 3003", *Journal of Manufacturing Systems* Volume 25, Issue 3, 2006, Pages 221-238
12. G. D. Janaki Ram, Y. Yang, B. E. Stucker, C. Robinson, "Use of Ultrasonic Consolidation for Fabrication of Multi-Material Structures", *Rapid Prototyping Journal*, Vol. 13/4, 2007, pp. 226–235.
13. Irfan Kaya, Omer Necati Cora, Dogan Acar, Muammer Koc, "On the Formability of Ultrasonic Additive Manufactured Al–Ti Laminated Composites", *Metallurgical and Materials Transactions A*, 03 July, 2018, Volume 49.
14. P. J. Wolcott, A. Hehr, M. J. Dapino, C. Pawlowski, "Process Improvements and Characterization of Ultrasonic Additive Manufactured Structures," *Journal of Materials Processing Technology*, Vol. 233,

2016, pp. 44–52.

15. C. Y. Kong, R. C. Soar, P. M. Dickens, “An Investigation of the Control Parameters for Aluminum 3003 under Ultrasonic Consolidation”, The University of Texas at Ausin, 2002.
16. Gowtham Venkatraman, Adam Hehr, Leon M. Headings, Marcelo J. Dapino, “Effect of System Compliance on Weld Power in Ultrasonic Additive Manufacturing”, Rapid Prototyping Journal © Emerald Publishing Limited [ISSN 1355-2546] [DOI 10.1108/RPJ-07-2020-0168]
17. Thongchai Arunchai, Phisut Apichayakul, Kreangsak Tamee, Kawin Sonthipermpon, “Resistance Spot Welding Optimization Based on Artificial Neural Network”, International Journal of Manufacturing Engineering, 09 November 2014.
18. Samah Sabah Barrak, Abbas Khammass Hussein, Sabah Khammass Hussein, Mohammed Helan Sar, Mursal Luaibi Saad, “Using Brass Foil Interlayer to Improve the Resistance Spot Welding AA5451 with Applied Taguchi Method,” Journal of Mechanical Engineering Research & Developments (JMERE), Vol. 42, Issue 3, 2019, pp. 120–124.
19. S. Hollatz, A. Olowinsky, A. Gillner, P. Heinen, E. Limpert, “Overlap Joining of Aluminum and Copper Using Laser Micro Welding with Spatial Power Modulation”, Welding in the World, Volume 64, 28 January 2010.
20. Sooriyamoorthy Elangovan, V. Jaiganesh, K. Prakasan, “Optimization of Ultrasonic Welding Parameters for Copper to Copper Joints Using Design of Experiments”, International Journal of Manufacturing Engineering, 2014.